ARCTIC
VOL. 71, NO. 2 (JUNE 2018) P. 149–166
https://doi.org/10.14430/arctic4716

Seasonal Variations in the Limnology of Noell Lake in the Western Canadian Arctic Tracked by In Situ Observation Systems

Benjamin Paquette-Struger,[1,2] Frederick J. Wrona,[1] David Atkinson[1] and Peter Di Cenzo[3]

(*Received 18 July 2017; accepted in revised form 29 January 2018*)

ABSTRACT. Research investigating climate-driven changes in northern lake ecosystems is complicated by a legacy of initiatives that have used sporadic observations, often confined to open-water seasons, to define the lake state. These observations have conventionally been lake water samples analyzed for a suite of physical and chemical parameters and are indicative of only the days or hours immediately before sampling. Monitoring approaches that sample a broader scope of limnological parameters over a continuous period are needed to augment existing strategies. A study of the seasonal changes to limnological parameters in Noell Lake was performed by analyzing continuous, hourly data collected from a series of automated and non-automated moorings over the period July 2012 to July 2013. Noell Lake was found to be strongly stratified throughout the open-water and under-ice seasons, with two prominent mixing periods in spring and fall. Processes of cryoconcentration and respiration intensified density-driven stratification while the lake is ice-covered, with the deep holes of Noell Lake becoming particularly saline and oxygen-depleted all year. Hypoxia was prevalent during the under-ice season because these physical and biogeochemical processes eliminated mixing from the lower lake depths while oxygen demand remained high. Use of continuous hourly monitoring facilitated improved understanding of the dynamical response of Noell Lake to atmospheric forcing.

Key words: limnology; continuous monitoring; mixing; stratification; dissolved oxygen; hypoxia

RÉSUMÉ. Les recherches sur les changements d'ordre climatique dans les écosystèmes lacustres nordiques sont compliquées par les incidences d'initiatives ayant recouru à des observations sporadiques, souvent restreintes aux saisons d'eaux libres, pour définir l'état des lacs. Habituellement, ces observations se sont traduites par l'analyse d'échantillons d'eau lacustre en fonction d'un ensemble de paramètres physiques et chimiques et par conséquent, elles ne sont représentatives que des jours ou des heures précédant immédiatement l'échantillonnage. Il y a lieu d'adopter des méthodes de surveillance qui permettent d'échantillonner de plus vastes paramètres limnologiques sur une période continue afin de rehausser les stratégies actuelles. L'étude des changements saisonniers à l'égard des paramètres limnologiques du lac Noell a été effectuée par le biais de l'analyse de données horaires et continues recueillies à partir d'une série d'amarrages automatisés et non automatisés pendant la période allant de juillet 2012 à juillet 2013. Cette étude a permis de déterminer que le lac Noell est fortement stratifié pendant les saisons d'eaux libres et d'englacement, et qu'il y a deux périodes de brassage importantes au printemps et à l'automne. Les processus de cryoconcentration et de respiration ont intensifié la stratification attribuable à la densité lorsque le lac est couvert de glace, les trous profonds du lac Noell devenant particulièrement salins et dépourvus d'oxygène pendant toute l'année. Pendant la saison d'englacement, l'hypoxie était répandue parce que ces processus physiques et biogéochimiques éliminaient le brassage dans les grandes profondeurs du lac alors que la demande en oxygène restait grande. Le recours à la surveillance horaire continue a permis de mieux comprendre la réponse dynamique du lac Noell au forçage atmosphérique.

Mots clés : limnologie; surveillance continue; brassage; stratification; oxygène dissous; hypoxie

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

In recent decades, the high latitudes of the Northern Hemisphere have warmed more than any other region on earth (Burrows et al., 2011), a trend that is expected to continue (Diffenbaugh and Giorgi, 2012; Collins et al., 2013). The Intergovernmental Panel on Climate Change (IPCC) has identified Arctic lakes as being one of the aquatic habitats most susceptible to direct climate effects, especially rising air temperatures (Settele et al., 2014), since the features of Arctic limnological systems are defined by air temperatures being persistently lower than 0˚C for the majority of the year (Vincent et al., 2012). Arctic lakes and ponds can serve as reference ecosystems against which

[1] Department of Geography, University of Victoria, PO Box 1700, Station CSC, Victoria, British Columbia V8W 2Y2, Canada
[2] Corresponding author: baps@uvic.ca
[3] Water & Climate Impacts Research Centre, Environment Canada, University of Victoria, PO Box 3060, Station CSC, Victoria, British Columbia V8V 3R4, Canada

recent and future global environmental change can be compared (Lim and Douglas, 2003).

Recent limnological investigations undertaken across the circumpolar Arctic have included sites in Alaska (e.g., LaPerriere et al., 2003), the western Canadian Arctic (e.g., Ogbebo et al., 2009a, b), the eastern Canadian Arctic (e.g., Westover et al., 2009), Finland (e.g., Luoto, 2009), Greenland (e.g., Cremer et al., 2005), Norway (e.g., Løvik and Kjellberg, 2003), Russia (e.g., Moiseenko et al., 2009), and Sweden (e.g., Brunberg et al., 2002). However, continuous monitoring programs of Arctic freshwater ecosystems have not been undertaken because of the financially and logistically prohibitive nature of northern research.

Continuous sampling has been challenging to undertake and sustain in Arctic lakes since they are generally far away from towns or established centres of human activity (MacDonald et al., 2012), and study sites are commonly accessible only by snowmobile or helicopter. Investigations of climate-driven changes in northern lake ecosystems are complicated by a patchwork of initiatives that have been forced to use sporadic observations, often confined to open-water seasons, to define the lake state (Bailey et al., 2004). These instantaneous observations have conventionally involved analysis of lake water samples for traditional physical and chemical parameters indicative of the days or hours immediately before sampling (Bailey et al., 2004). Investigations that sample parameters continuously over an extended period are needed to define the state and long-term natural variability of these systems accurately (Antoniades et al., 2005; MacDonald et al., 2012) and address key questions related to climate and environmental change in Arctic regions (Smol and Douglas, 2007). Recently, Deshpande et al. (2015) used continuous automated measurements to investigate hourly, seasonal, and depth differences in oxygen concentrations in Quebec thaw lakes.

This study aimed to obtain continuous measurements of limnological parameters in Noell Lake over the course of a year in order to understand the processes that regulate the characteristics of an upland tundra lake in the western Canadian Arctic. In particular, we charted baseline limnological progression over the course of a year, with special attention paid to the under-ice season. Our second aim was to analyze results in the context of identifying processes that are expected to change as a result of warming of high-latitude northern lakes, processes which can best be monitored by evaluating the extent of seasonal variations in hypoxia linked to stratification, mixing, and oxygen depletion and ascertaining natural variability.

To address these objectives, we deployed automated and non-automated in situ sensors that recorded hourly measurements of water temperature, specific conductivity, dissolved oxygen, percent saturation of dissolved oxygen, and pH. We also sampled lake water quality and water chemistry in successive seasons and recorded lake depth profiles during the open-water season and under-ice conditions.

METHODS

Study Site

Noell Lake (68˚31′37″ N, 133˚30′48″ W) is located 15.0 km NE of Inuvik, Northwest Territories (NWT), and just north of the tree line (Ogbebo et al., 2009a). Situated 89.9 m above sea level, this oval upland tundra lake (Fig. 1) lies east of the Mackenzie River Delta in the western Canadian Arctic (de Rham and Carter, 2009). Despite its close proximity to the Mackenzie River, Noell Lake is geomorphically and hydrologically separated from this large river system (Ramlal et al., 1991). The waterbody is situated in a lake-rich area and underlain primarily by expanses of continuous permafrost (Pienitz et al., 1997a). Beneath the permafrost is bedrock composed primarily of carbonate and shale (Kokelj et al., 2005), and soils are dominated by Wisconsinan tills derived from this bedrock (Houben et al., 2016). Noell lake has a surface area of 30.0 km^2 and a maximum depth of 18.3 m (Fig. 1) (de Rham and Carter, 2009). It has a single outflow, Jimmy Creek, which flows northward from Noell Lake into Jimmy Lake (Read and Roberge, 1986). There are no islands in Noell Lake, and industrial development in the catchment area had been minimal until the construction of an all-season road began in the spring of 2013.

Prominent lake features include three deep holes located in the northeast and southwest quadrants of the lake (Fig. 1). The northeast quadrant contains two of the three holes; the more westerly hole is approximately 15 m deep, and the hole to the east of the quadrant is approximately 16 m deep. The hole in the southwest quadrant is the deepest part of Noell Lake, extending to a depth of 18 m. The northwest and southeast quadrants are shallower than the northeast and southwest quadrants. Maximum depth is approximately 8 m in the northwest quadrant and only 6 m in the southeast quadrant. In general, the lake bottom of Noell Lake slopes gradually from the shoreline inwards, except on the western and northeastern shores, where considerably steeper slopes exist.

Noell Lake is situated within the Arctic tundra ecological zone (Ogbebo et al., 2009a). The various boreal and tundra flora, grasses, dwarf shrubs, herbs, lichens, mosses, and sedges that characterize the vegetation of the region are small, reflecting their adaptation to the short growing seasons distinguishing the area (Ogbebo et al., 2009a, b). The vegetative community of the Noell Lake region also includes Labrador Tea (*R. tomentosum*) and assorted berries, although these are considerably less abundant (Quinton and Marsh, 1999). The closest Environment Canada weather station is located at the Inuvik airport (15 km away). For the period 2007–12, annual daily average air temperature was −7.1˚C (Environment Canada, 2012). Average January air temperature was −24.9˚C, and average July air temperature was 14.9˚C. Average annual precipitation was 201.6 mm, with the greatest proportion falling as rain during the summer months.

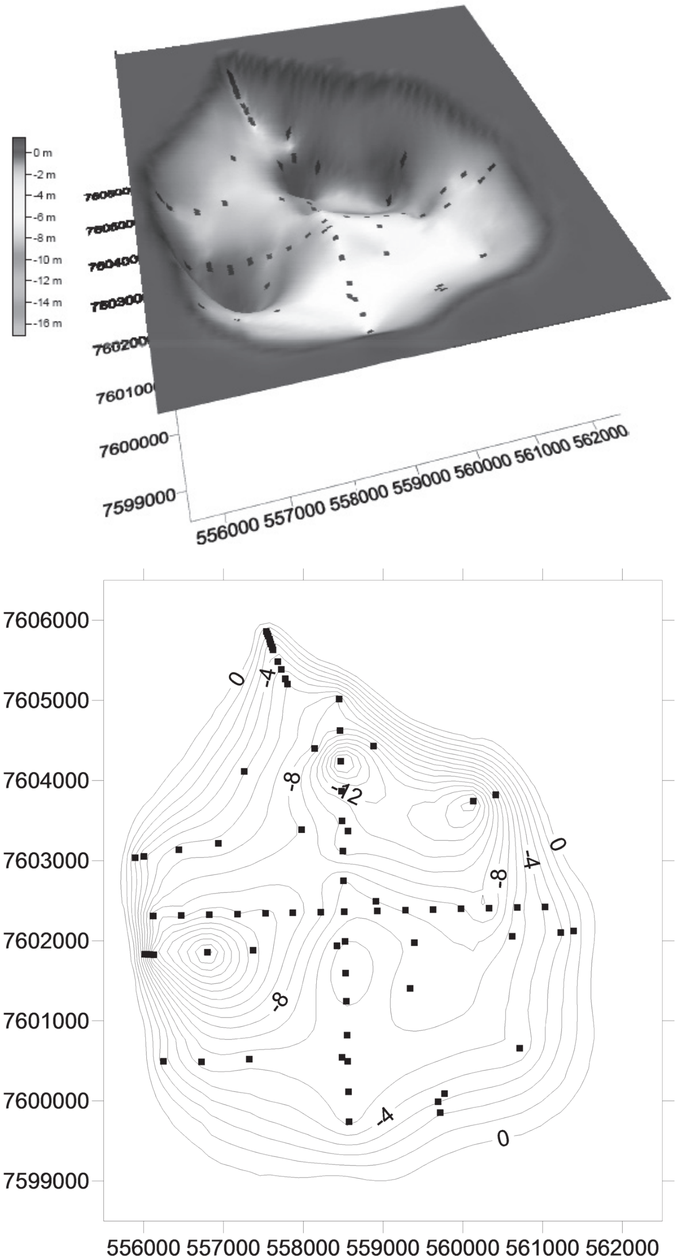


FIG. 1. Surface (top) and contour (bottom) maps of Noell Lake bathymetry. Survey points are included; top figure vertical exaggeration = 166. Data from de Rham and Carter (2009).

The limnology and ecology of Noell Lake were first studied during the open-water seasons of 1982 and 1983 (Read and Roberge, 1986). Additional hydro-ecological investigations were undertaken at Noell Lake, as well as other lakes and channels in the region, between 1985 and 1987 (Anema et al., 1990a, b). Noell Lake was sampled during lake-transect investigations by Pienitz et al. (1997a, b), who gathered water chemistry and other associated limnological data for 59 lakes in Yukon and the NWT. Ogbebo et al. (2009a, b) gathered information on the general limnology and geochemical characteristics of 30 lakes (including Noell Lake) situated along the proposed Mackenzie Gas Project pipeline route in the NWT.

Compared to other non-flooded western Arctic tundra lakes sampled by Ogbebo et al. (2009a), Noell Lake contained some of the lowest ionic concentrations, e.g., conductivity, Na, Cl, SO_4, and dissolved inorganic carbon (DIC). Ogbebo et al. (2009a) determined that parameters encompassing the ionic concentrations of water (i.e., conductivity, Na, Cl, Ca, SO_4, and DIC) were positively correlated with each other and negatively correlated with both elevation and latitude. Noell Lake was the farthest south and the second highest in elevation of the nine lakes investigated, which may explain why ionic concentrations were low. The southern extent of Noell Lake means it is relatively far from the ionic inputs of the Arctic Ocean (Evans and Grainger, 1980). Additionally, its surface elevation is 89.9 m ASL (de Rham and Carter, 2009; Ogbebo et al., 2009a) and thus Noell Lake does not undergo the regular flooding that adjacent lakes below 5 m ASL experience (Ogbebo et al., 2009a). Using particulate organic carbon (POC) to chlorophyll-a ratios, Ogbebo et al. (2009b) determined that Noell Lake relies mainly on autochthonous sources of carbon.

Automated Continuous In Situ Measurements

An integrated continuous monitoring program of the hydro-ecology of Noell Lake was established using a multi-component Arctic Lake Monitoring System (ALMS) deployed from 28 September 2010 until 2 July 2013. The ALMS collected continuous in situ time series of key climatological, hydrological, chemical, and biological parameters during both open-water and under-ice seasons and in both the epilimnion and hypolimnion (68˚31’37″ N; 133˚30′48″ W). The ALMS consisted of three separate instrument assemblies that were deployed and removed, one after another, in the same location: the site of the deepest hole in Noell Lake. The primary automated Arctic lake buoy and subsurface mooring system (Fig. 2) was deployed first, followed by the supplementary subsurface mooring system and the instrumented subsurface mooring (Fig. 3). All three used the same multi-parameter water quality sondes (Yellow Springs Instruments [YSI] Model 6600).

The primary automated subsurface mooring consisted of a frame onto which two sondes were mounted in a vertical profile at 3 m and 9 m below the lake surface. The supplementary subsurface mooring system also consisted of two vertically arrayed sonde assemblies mounted at the same depths (3 m and 9 m) as those of the primary system. The instrumented subsurface mooring system was designed at the University of Victoria but assembled in Inuvik. We used spring-loaded gate carabiners to attach three sonde assemblies (at depths of 3 m, 5 m, and 9 m) to knotted loops in a cable extending from an anchor at the bottom of the lake to a marine float device at the surface. HOBO data loggers (Onset Computer Corp.; temperature resolution and accuracy: 0.02˚C and ± 0.21˚C) were programmed to record hourly water temperature and strapped to the cable with plastic cable ties at 1 m intervals.

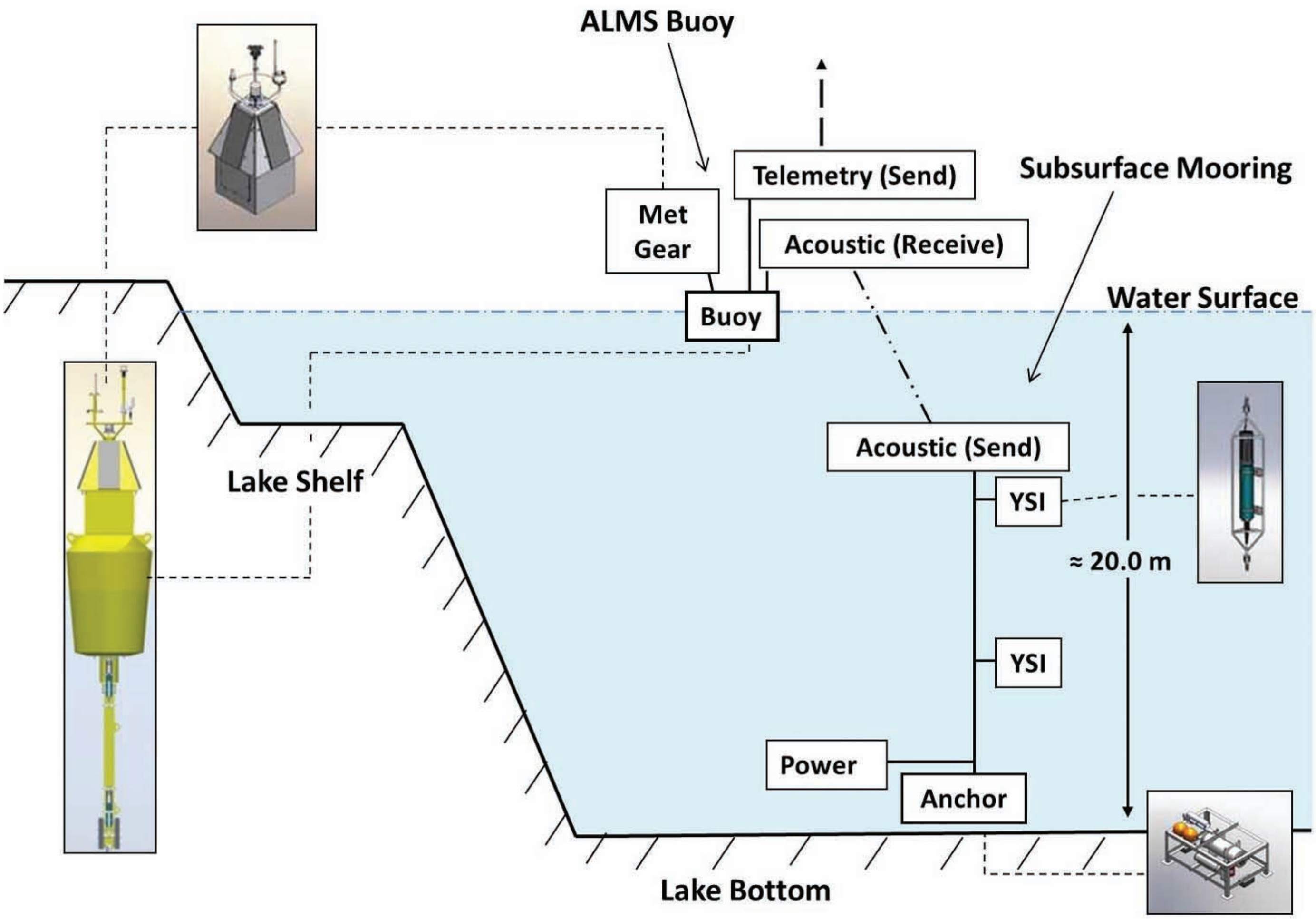


FIG. 2. Schematic representation of the ALMS buoy and subsurface mooring system deployed in Noell Lake, NWT. Meteorological (Met) Gear: Anemometer – windspeed; temperature and relative humidity sensors; pyranometer – radiation; barometer – pressure. Yellow Springs Instruments, water quality sonde.

Installed on the water quality sondes were sensors for water temperature (YSI Model 6560 sensor; temperature resolution and accuracy: 0.01˚C and ± 0.15˚C), conductivity (YSI Model 6560 sensor; conductivity resolution and accuracy: 0.001 to 0.01 mS/cm and ± 0.5% of reading + 0.001 mS/cm), percent saturation of dissolved oxygen (ROX™ Optical Dissolved Oxygen, YSI; oxygen resolution and accuracy: 0.1% and ± 1% of reading), concentration of dissolved oxygen (ROX™ Optical Dissolved Oxygen, YSI; oxygen resolution and accuracy: 0.01 mg/L and ± 0.1 mg/L), and pH (6561 Sensor, YSI; pH resolution and accuracy: 0.01 unit and ± 0.2 unit).

Lake Sampling

Previous unpublished investigations suggested an overwinter ice thickness of more than 2.0 m. As a result, bulk water quality samples were collected at a 3 m depth from seven locations on Noell Lake and analyzed for a suite of chemical and nutrient parameters (Fig. 4). Five different lake sampling campaigns were undertaken for chemical analysis (on 17 September 2011, 13 May 2012, 26 June 2012, 19 November 2012, and 15 July 2013) and four for nutrient analysis (on 17 September 2011, 13 May 2012, 19 November 2012, and 15 July 2013). Noell Lake was accessed via helicopter, and sampling was conducted by boat using a Van Dorn Sampler. Upon retrieval, all water samples were immediately placed in coolers containing ice packs. Samples were filtered at the Aurora Research Institute in Inuvik, NWT, and prepared for transport to analytical laboratories capable of performing the necessary analyses within 24 hours of removal.

Chemical analyses were performed at the National Laboratory for Environmental Testing in Burlington, Ontario and included specific conductivity (Spec. cond.), pH, alkalinity (Alk.), major anions (F, Cl, SO_4), colour, dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), hardness (Hard.), major cations (Ca, Mg, Na, K), nitrogen dioxide (NO_2), silica (SiO_2), and turbidity (Table 1). Nutrient analyses were performed at the National Laboratory for Environmental Testing in Saskatoon, Saskatchewan, and included dissolved phosphorus (DP), ammonia (NH_3), nitrate-nitrite (NO_3NO_2), soluble reactive phosphorus (SRP), particulate organic carbon (POC), particular organic nitrogen (PON), total nitrogen (TN), total phosphorus (TP), total dissolved nitrogen (TDN),

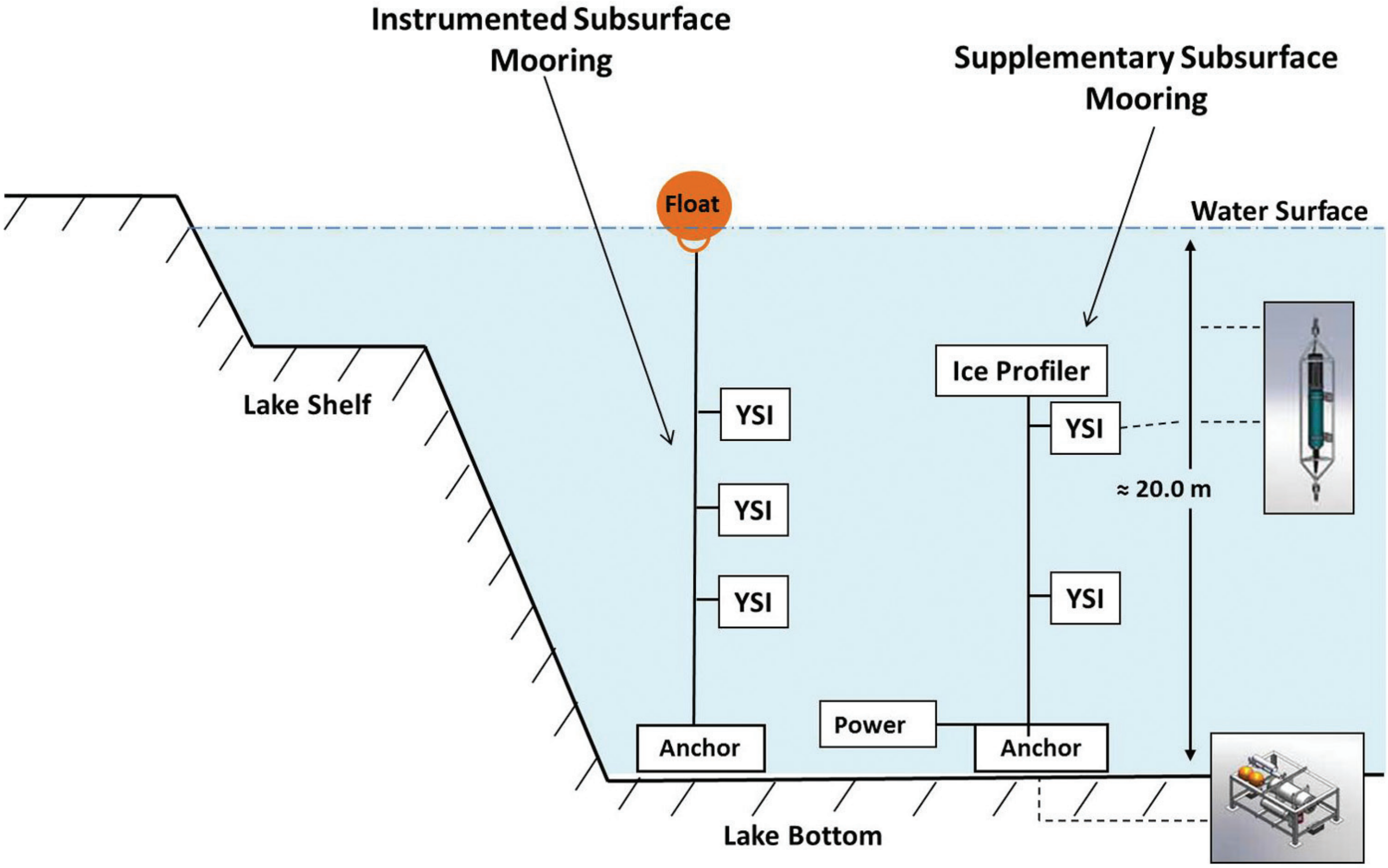


FIG. 3. Schematic representation of the supplementary subsurface mooring (right) and instrumented subsurface mooring (left) deployed in Noell Lake, NWT. Yellow Springs Instruments, water quality sonde.

turbidity, and colour (Table 2). Both laboratories followed standard protocols, as delineated by Environment Canada (1992). The abbreviations used above correspond to labels that will be used in subsequent tables and figures.

Water Column Profiles

Collection of instantaneous depth profiles of limnological measurements was timed to correspond to mixing and stratification events. A handheld (YSI 556) YSI Multiparameter Water Quality Sonde Assembly was used to record depth-profiles of water temperature, specific conductivity, dissolved oxygen, percent saturation of dissolved oxygen, and pH at 1 m intervals, in open-water and under-ice conditions. The YSI sensors used were identical to those of the subsurface mooring systems.

RESULTS

Open Water

In early August 2012, air temperatures declined and hypolimnion temperatures converged with those of the epilimnion, eliminating the thermal stratification that had inhibited mixing between the upper and lower zones of the lake (Fig. 5a). Once lake water temperatures were isothermal, even moderate wind action mixed the entire lake volume; a full-lake mixing event took place on 12 August 2012—the day of the maximum daily average hypolimnion temperature. Immediately after this event, epilimnion and hypolimnion water temperatures diverged once more. On 26 August 2012, epilimnion temperatures approached those of the hypolimnion and eliminated stratification once again. Both of the whole-lake mixing events could be inferred from the decline and resupply of dissolved oxygen (Fig. 5c), as well as the percent saturation of dissolved oxygen (Fig. 5d).

The epilimnion remained well oxygenated throughout the 2012 open-water season (Fig. 5c, d) as a result of free exchange with the atmosphere that facilitated a consistent resupply of oxygen into the well-mixed epilimnion, as well as sustained photosynthetic production and decreasing water temperatures in this well-lit zone. Conversely, both the percent saturation and concentration of dissolved oxygen steadily decreased in the hypolimnion during the open-water period of stratification.

During stratification, the hypolimnion was, in effect, closed off from interacting with the atmosphere. The diffusion of oxygen from the epilimnion into the depleted

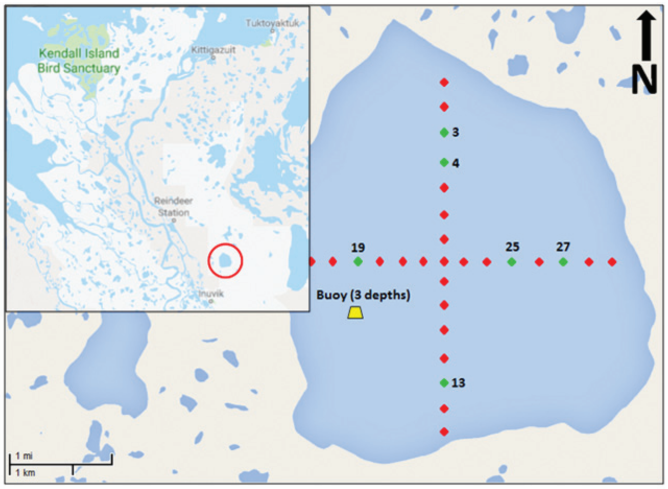


FIG. 4. Schematic representation of locations for the ice survey (red diamonds) and water sampling (green diamonds) in Noell Lake. Additional water samples were taken at a site near the ALMS Buoy (yellow trapezoid). The inset shows the location of Noell Lake (circled in red) in the context of Inuvik, NWT, and the Mackenzie Delta uplands.

hypolimnion is slow, and thus a mixing event was the likely cause of the sudden increase in hypolimnetic dissolved oxygen saturation that began on 10 August 2012. As previously mentioned, stratification was re-established on 18 August 2012, and dissolved oxygen decreased again. A second mixing event was observed on 25 August 2012, and summer stratification was eliminated for the duration of the 2012 open-water season. The stratification and mixing events were corroborated by water temperature data recorded by HOBO dataloggers strapped to the cable of the instrumented subsurface mooring.

Once stratification was eliminated, Noell Lake remained relatively well mixed and isothermal for the rest of the 2012 open-water period, and the water temperatures of the epilimnion and hypolimnion cooled simultaneously (Fig. 5a, c, d). Full mixing of the lake water column persisted from 26 August 2012 until 23 October 2012, when ice began to form on the lake and winter stratification commenced.

TABLE 1. Average concentrations of major ions and related water quality variables for Noell Lake for selected seasons and months (1982–2013). Average concentrations are in mg L^{-1} except for pH in pH units, water temperature in (˚C), and specific conductivity in (µS cm^{-1}).

	August 1982[1]	Summer 1986[2]	July 2007[3]	September 2011	May 2012	June 2012	November 2012	July 2013
pH	–	7.6	8.2	7.4	7.3	7.2	7.2	7.3
Water temp.	13.5	10.2	15.7	–	–	–	–	–
DO	9.0	–	9.8	–	–	–	–	–
Spec. cond.	–	71.1	67.3	71.2	89.4	71.1	79.0	79.9
Mg	1.2	2.0	–	2.1	2.6	2.2	2.4	2.1
Na	1.9	2.4	2.5	2.4	3.0	2.5	2.8	2.5
K	0.6	1.0	–	1.0	1.2	1.1	1.1	1.1
Cl	2.4	2.1	1.7	1.7	2.2	1.8	2.1	1.8
Ca	4.7	7.0	7.1	7.0	8.7	6.9	7.4	7.3
SO_4	9.5	10.9	11.0	11.4	14.3	11.1	12.5	11.3
SiO_2	–	–	0.4	0.22	0.37	0.36	0.23	0.6
Fe	–	0.04	–	–	–	–	–	–
Mn	–	0.01	–	–	–	–	–	–

[1] Data from Read and Roberge (1986).
[2] Data from Anema et al. (1990b).
[3] Data from Ogbebo et al. (2009a).

TABLE 2. Average concentrations of nutrient, chlorophyll-a, and Secchi depth data for Noell Lake for selected seasons and months (1982–2013). Average concentrations are in µg L^{-1} unless designated otherwise.

	August 1982[1]	Summer 1986[2]	July 2007[3]	September 2011	May 2012	November 2012	July 2013
Secchi depth (m)	–	–	2.8	–	–	–	–
TP	–	–	7.8	12.5	4.5	4.7	8.6
DP	70.0	–	1.8	2.7	2.7	2.0	2.3
TN	–	–	201.5	329.0	259.0	220.0	251.0
TDN	1000.0	–	192.8	–	–	–	–
NH_3	–	–	6.3	5.6	9.8	4.6	12.9
Nitrate	–	–	5.0	1.0	29.0	2.4	1.0
Chlorophyll a	0.3	0.8	1.6	–	–	–	–
POC	–	–	103.0	869.0	51.9	–	190.0
DOC (mg/L)	–	–	4.9	6.33	6.44	–	5.7
DIC (mg/L)	–	–	4.3	4.2	5.73	4.34	4.1

[1] Data from Read and Roberge (1986).
[2] Data from Anema et al. (1990b).
[3] Data from Ogbebo et al. (2009a).

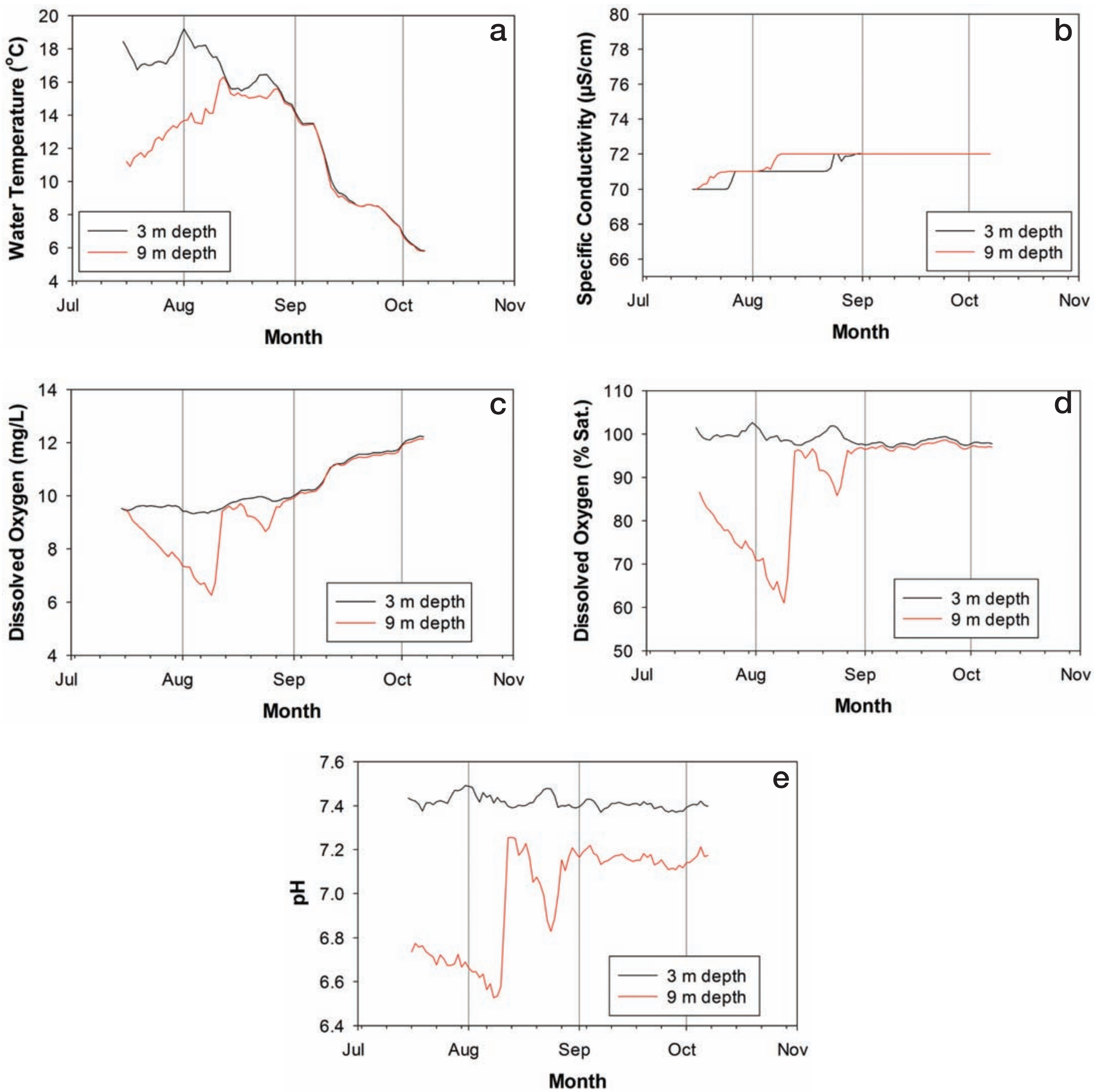
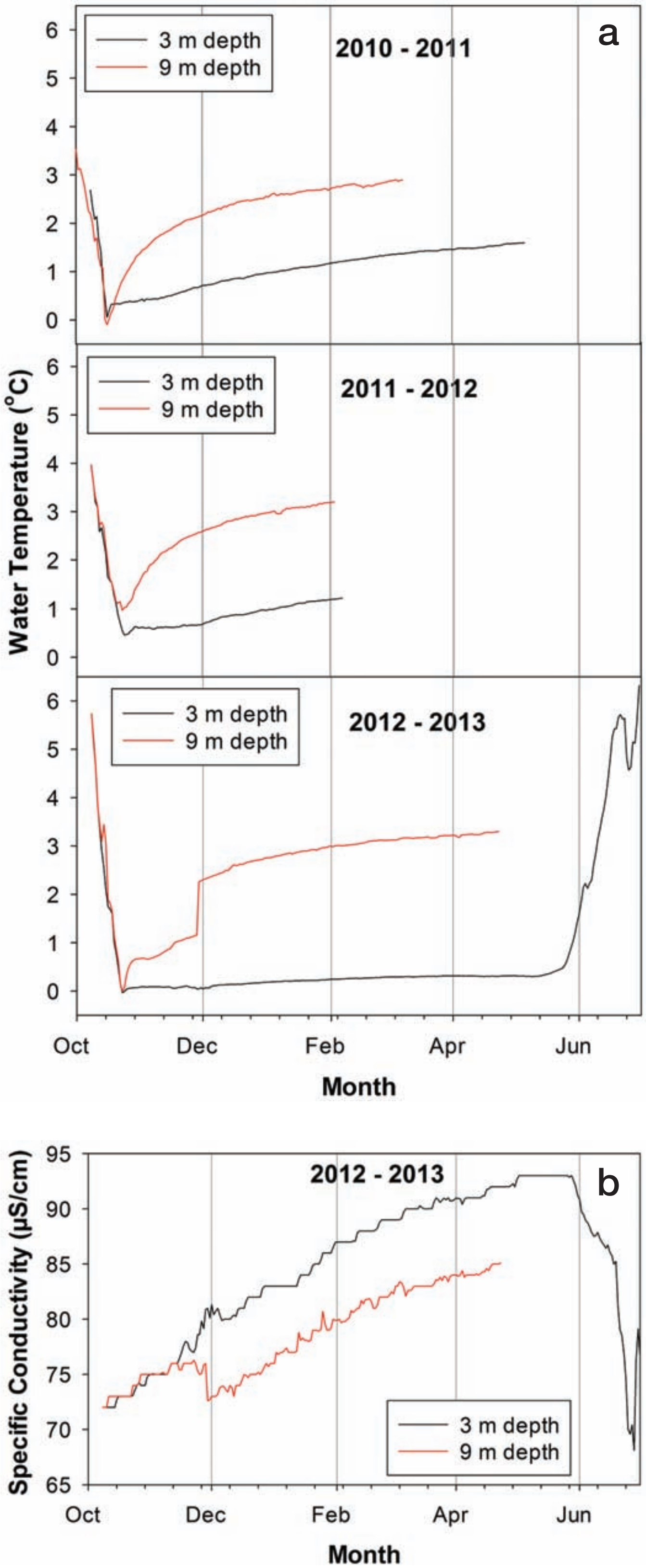


FIG. 5. Plots of continuous limnological measurements recorded by various buoy and mooring components of the Arctic Lake Monitoring System during the 2012 open-water period. The black line represents parameter values recorded at a depth of 3 m below the water surface. The red line represents parameter values recorded at a depth of 9 m below the water surface.

Under Ice

Prior to lake ice formation on Noell Lake, the density difference between water at 0˚C and water below 3˚C was relatively small, which means that mixing of the entire lake was likely caused and sustained by wind action. As a result, it was possible for the temperature of the entire lake body to approach 0˚C (Figs. 6a, 7). Once ice formed and covered Noell Lake, thermal exchanges with the atmosphere were reduced, and wind-induced mixing was essentially eliminated. Water immediately below the newly formed ice was 0˚C and underlain by water of increasing density and temperature.

Differences between epilimnion and hypolimnion water temperatures were less pronounced in winter than in the open-water season. Average hypolimnion temperatures during the three under-ice seasons ranged from 2.9˚C to 3.3˚C (Figs. 6a, 7). After the lake ice cover was in place,



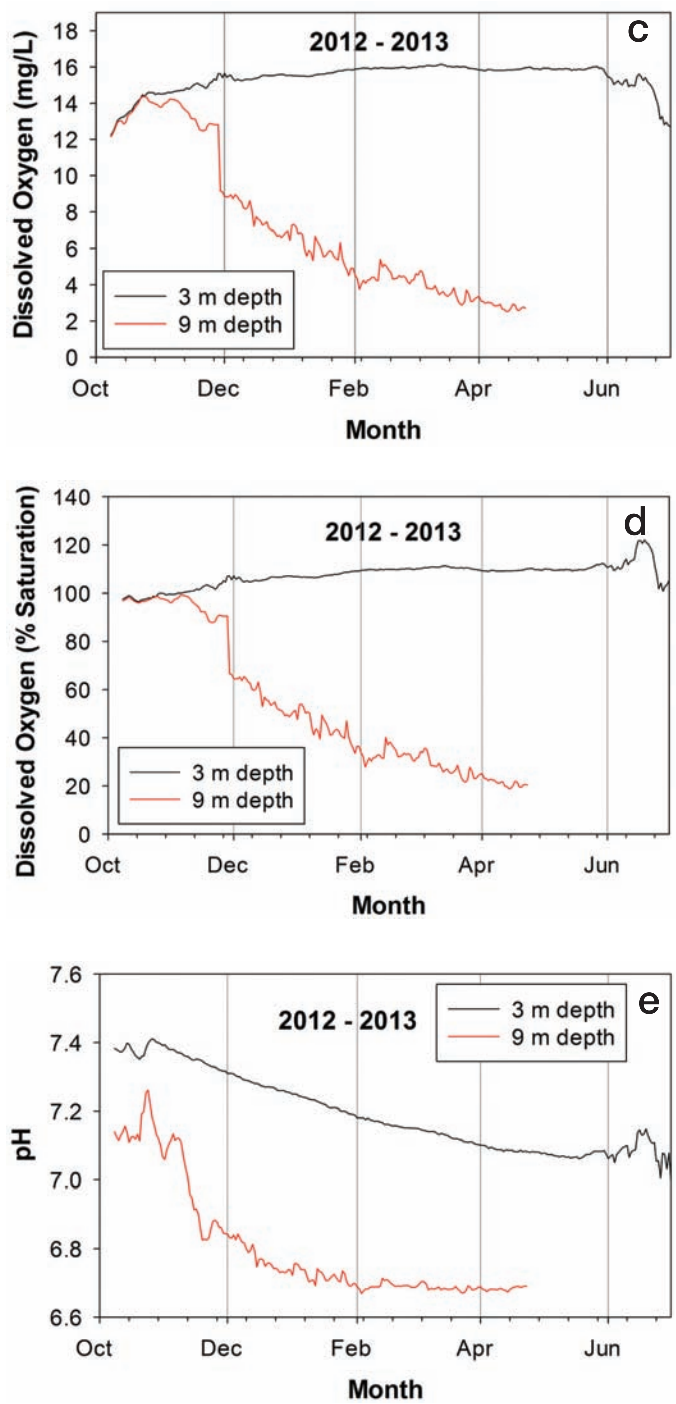


FIG. 6. Plots of continuous limnological measurements recorded by various buoy and mooring components of the Arctic Lake Monitoring System during several under-ice periods. The black line represents parameter values recorded at a depth of 3 m below the water surface. The red line represents parameter values recorded at a depth of 9 m below the water surface.

mixing ceased and lake-bottom water temperatures increased, warming more rapidly at the deeper levels.

Both the concentration and percent saturation of dissolved oxygen reached a maximum at the end of the under-ice season, when ice was likely thickest; conversely, hypolimnion concentrations were well below 5 mg/L, likely because of benthic respiration (e.g., Schindler et al., 1974; Welch, 1974). Hypoxia was attained in the hypolimnion on 3 March 2013, when the percent saturation of dissolved oxygen decreased to less than 30% (Fig. 6d). Dissolved oxygen declined until reaching 19.4% by the end of the ice-cover season, at which point concentrations of

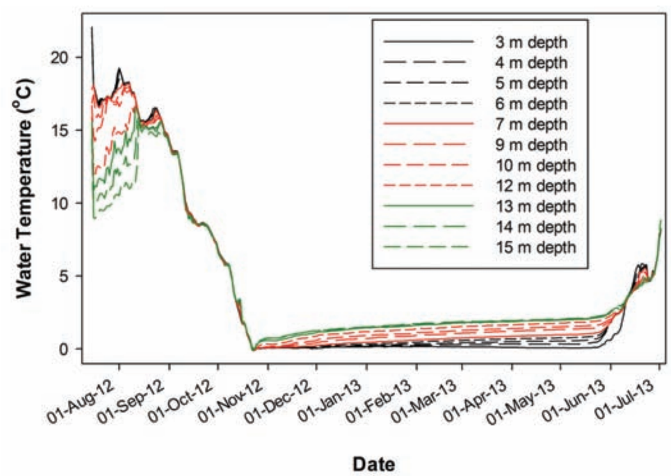


FIG. 7. Time series of water temperatures recorded by HOBO data loggers strapped at 1 m intervals to the cable of the instrumented subsurface mooring.

hypolimnetic dissolved oxygen had dropped to 2.5 mg/L (Fig. 6c). With the formation of ice cover on Noell Lake, the system was essentially sealed off from exchanges with the atmosphere (Wetzel, 1983). During this time, the density-driven movement of water from the epilimnion down to the hypolimnion was sufficiently slow that dissolved oxygen was depleted by the time it reached lower depths (Terzhevik et al., 2009).

A sharp increase in epilimnion temperature that occurred at the end of the 2012 – 13 under-ice season (Fig. 6a) is likely related to the breakup of the ice cover and return of radiative warming. Specific conductivity dropped abruptly just prior to June 2013, implying ice-out and the onset of mixing. While the YSI sondes installed on the buoy and mooring components did not record data long enough to capture mixing during spring turnover, analysis of measurements recorded by HOBO data loggers indicate full lake mixing occurred on 10 and 23 June 2013 (Fig. 7). These events resupplied oxygen to the depleted lake bottom.

There were two separate mixing periods in Noell Lake: (1) in June (under ice/during breakup) and (2) in August (open water). It is noteworthy that both mixing periods consisted of two separate mixing events with brief periods of stratification in between. Winter stratification persisted from 23 October 2012 until 10 June 2013. A slight decrease in pH values over the winter was likely due to the addition of CO_2 to the lake by respiration of the benthic community (Schindler et al., 1974); pH then increased with increased melt and runoff during the spring and summer (Figs. 5e, 6e).

Changes in Water Chemistry

Average concentrations of Mg ranged from 2.1 to 2.6 mg L^{-1}, while Na varied from 2.4 to 3.0 mg L^{-1} (Table 1). Concentrations of K, Cl, and Ca varied from 1.0 to 1.2 mg L^{-1}, 1.7 to 2.2 mg L^{-1}, and 6.9 to 8.7 mg L^{-1}, respectively. Concentrations of SO_4 ranged from 11.1 to 14.3 mg L^{-1}, while SiO_2 varied from 0.2 to 0.6 mg L^{-1}. Specific conductivity and concentrations of Mg, Na, K, Cl, Ca, and SO_4 were all highest during the lake-sampling campaign of May 2012, when Noell Lake was under full ice cover. Similarly, the second-highest recorded concentrations of these parameters occurred in November 2012, likely just after lake ice formation was initiated. The highest concentrations of ionic species being recorded under ice were likely a result of concentration by freeze-out (Schindler et al., 1974). Concentrations of SiO_2 were highest in July 2013.

Total phosphorus levels ranged from 4.5 to 12.5 µg L^{-1}, while dissolved phosphorus varied from 2.0 to 2.7 µg L^{-1} (Table 2). Total nitrogen levels varied from 220.0 to 329.0 µg L^{-1}. Levels of ammonia ranged from 4.6 to 12.9 µg L^{-1}, while levels of nitrate + nitrite varied from 1.0 to 29.0 µg L^{-1}. Dissolved organic carbon concentrations varied from 5.7 to 6.44 mg L^{-1} and those of dissolved inorganic carbon from 4.1 to 5.7 mg L^{-1}. Particulate organic carbon concentrations varied from 51.9 to 869.0 µg L^{-1}. Concentrations of total phosphorus, dissolved phosphorus, total nitrogen, and particulate organic carbon were highest in September 2011. Concentrations of dissolved organic carbon, dissolved inorganic carbon, ammonia, and nitrate + nitrite were highest in May 2012.

Full water chemistry data from all five lake sampling campaigns are given in online Appendix 1 (Tables S1 – S5).

Open-Water Vertical Profiles

Vertical profiles of limnological parameters (Fig. 8) were recorded on 8 August 2012 at the same seven locations used for lake sampling (Fig. 4). Water column temperatures remained in the range from 16.6˚C to 18.2˚C in the well-mixed upper 12 m of the lake, before rapidly cooling to 9.3˚C at 18 m. Specific conductivity ranged from 62.0 to 67.0 µS cm^{-1} in the upper 3 m of the lake, held constant with depth at 63.0 µS cm^{-1} until slightly decreasing from 12 m until the lake bottom (18 m). The percent saturation of dissolved oxygen remained between 93% and 100% in the upper 12 m of the lake, with a slight linear decrease with depth; below the stratified hypolimnion, the percent saturation of dissolved oxygen decreased abruptly to 60% near the bottom waters. The concentration of dissolved oxygen ranged from 9.0 to 9.5 mg L^{-1} in the upper 12 m of the lake and decreased to 6.9 mg L^{-1} by 18 m once it reached the sealed-off, stratified hypolimnion. Recorded pH values were as high as 8.1 at the surface and 7.1 at the lake bottom.

Under-Ice Depth Profiles

Under-ice depth profiles were recorded on 13 May 2012 (Fig. 9); these represent the first instantaneous under-ice depth profiles of limnological parameters recorded in Noell Lake. At the time of sampling, lake ice thickness ranged from approximately 1.0 to 2.0 m across the lake. The water column was fully stratified, and water temperature ranged

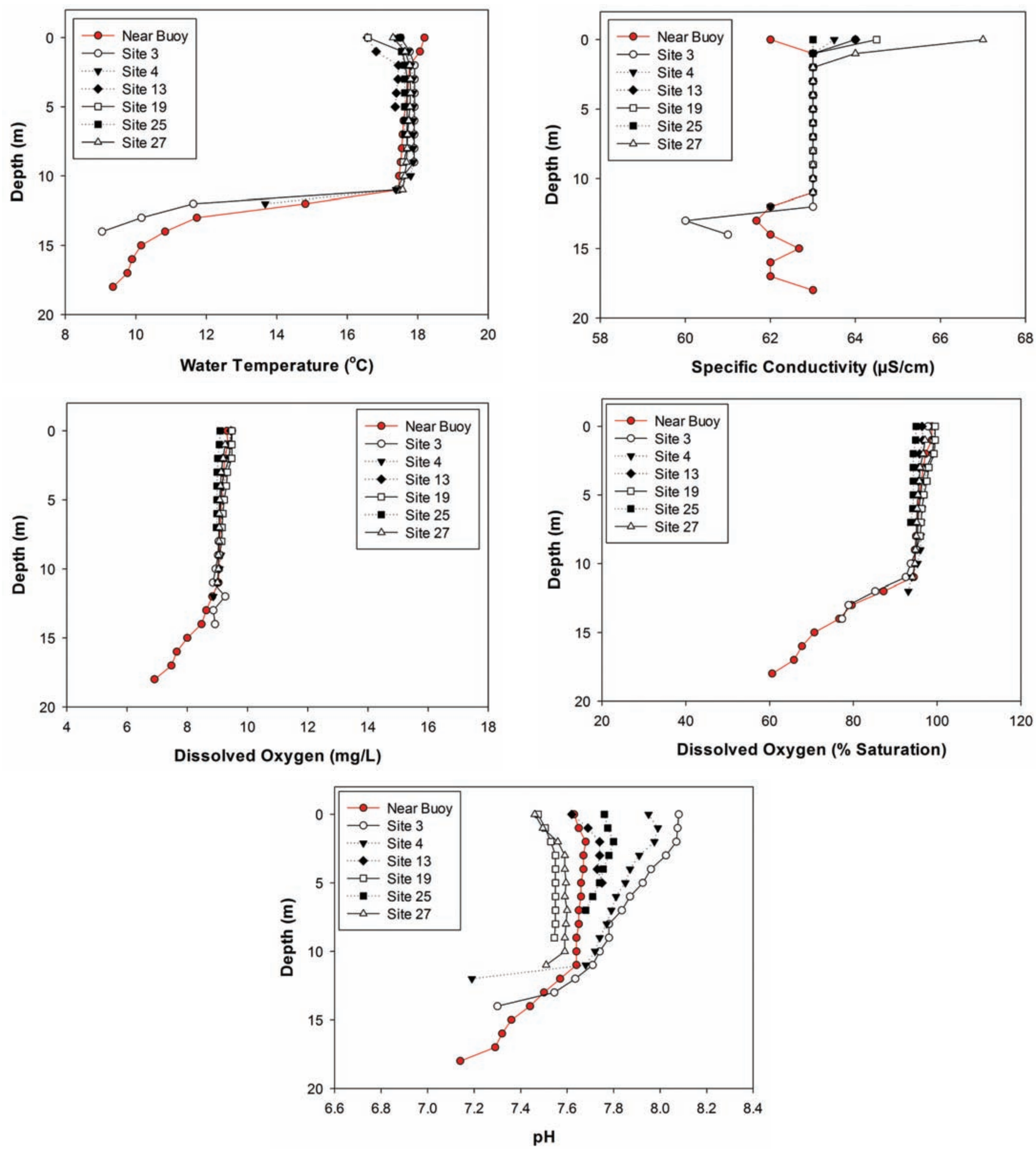


FIG. 8. Open-water depth profiles of a multitude of limnological parameters recorded by a hand-held water quality sonde at a multitude of locations in Noell Lake on 8 August 2012.

from 0.1˚C to 0.5˚C at 1.0 m (likely just below the ice) to 2.9˚C to 3.7˚C at a depth of 16 m. As in other northern lakes (e.g., Schindler et al., 1974), specific conductivity had two maxima during the period of active freezing, one just below the ice and the other at the lake bottom. Minimum specific conductivity was recorded in the 3–4 m depth zone and ranged from 77.9 to 97.0 µS cm^{-1}, whereas maximum values were recorded at a depth of 16 m and ranged from 92.0 to 100.0 µS cm^{-1}. Both the concentration and percent saturation of dissolved oxygen recorded under-ice maxima

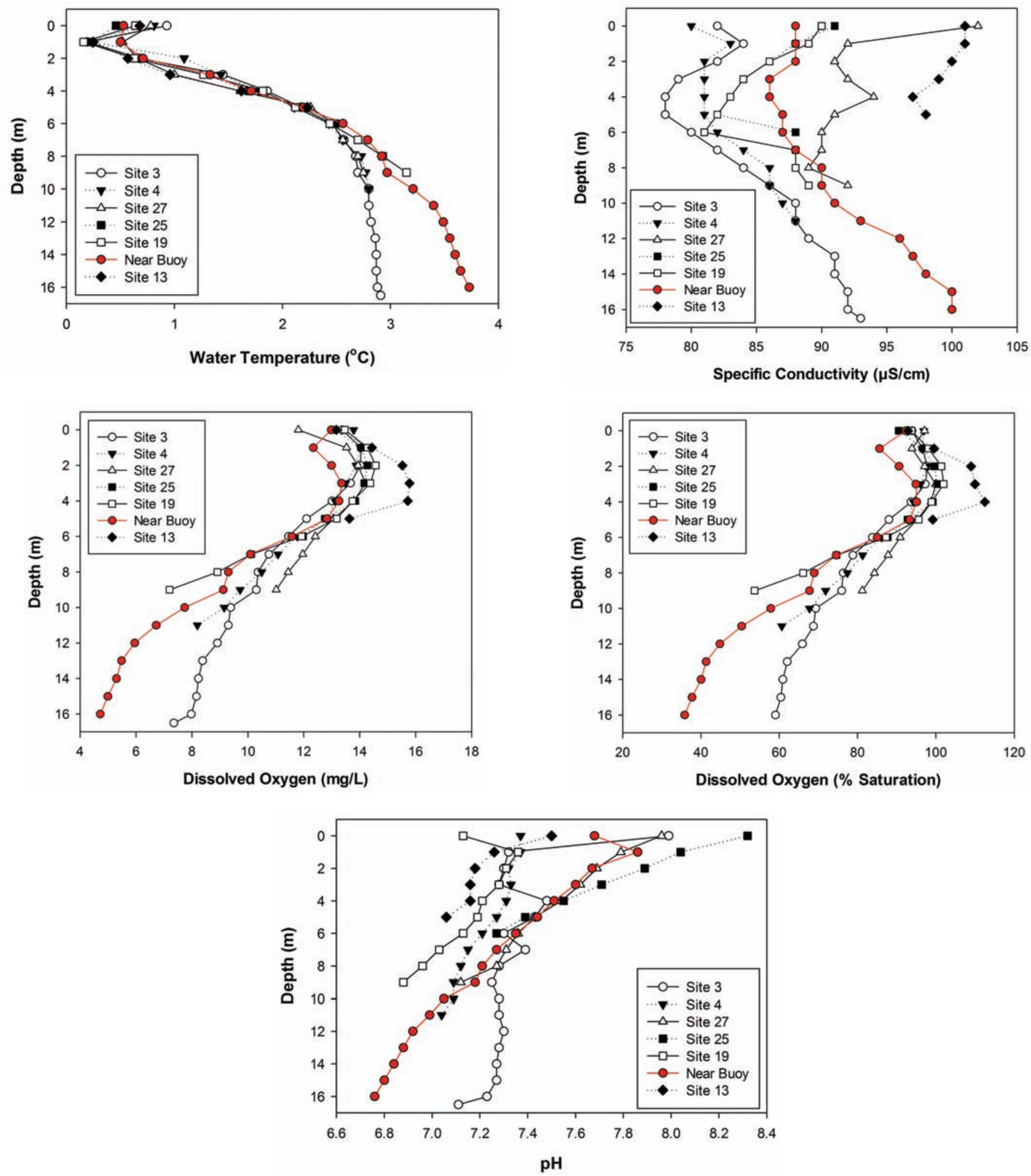


FIG. 9. Under-ice depth profiles of a multitude of limnological parameters recorded by a hand-held water quality sonde at a multitude of locations in Noell Lake on 13 May 2013.

in the 2 – 4 m range. Percent saturation of dissolved oxygen was 95% – 113% in the 3 – 4 m range and decreased to 35% – 59% by the lake bottom. Concentrations of dissolved oxygen displayed a maximum of 13.3 to 15.8 mg L^{-1} at 3 m and decreased to 4.6 to 8.0 mg L^{-1} at 16 m. pH ranged from 7.1 to 8.3 at the surface and from 6.8 to 7.2 near the bottom of Noell Lake.

DISCUSSION

Distinctive features of Noell Lake captured by continuous, automated sensors include short-term changes in thermal stratification that caused large changes in concentrations of dissolved oxygen, especially during the open-water season, and the existence and evolution of hypoxic conditions under the ice. Concentrations of dissolved oxygen decreased to well below 5.0 mg L^{-1} during the under-ice season. This decrease contrasts with observations taken at Toolik Lake, Alaska, where dissolved oxygen concentrations remained between 8.0 and 12.0 mg L^{-1} from the upper water column until the lowest sampling depth of 16 m (Whalen and Cornwell, 1985).

Lake water sampling revealed the significance of cryoconcentration processes related to increased ionic species in lake water. The under-ice data recorded during this study are rare, and the first of their kind from Noell Lake. Additionally, a limnologically significant event was captured in late November 2012; changes to several key limnological variables over a 24-hour period accounted for one-third of the total range observed during the under-ice season (discussed below). The stratification of Noell Lake persisted for the duration of the under-ice season and was corroborated by observable declines of dissolved oxygen (Fig. 6c), as well as by the marked increases in specific conductivity at the lake bottom; Deshpande et al. (2015) reported similar findings in Quebec thaw lakes.

Biogeochemical Implications

Concentrations of major ions in Arctic lakes exhibit substantial seasonal fluctuations due to offsetting processes of dilution and concentration (e.g., Welch and Legault, 1986; Cornwell, 1992). In the springtime, snowmelt contributes runoff into lakes and overall concentrations of ions are diluted; conversely, ion concentration occurs as a result of exclusion by evaporation (in the summer) and ice formation (in the winter) (Hobbie, 1984; Kling et al., 1992), likely contributing to overall increases in specific conductivity during under-ice seasons (e.g., Schindler et al., 1974; Welch and Bergmann, 1985; Belzile et al., 2002; Deshpande et al., 2015). In Noell Lake, concentrations of Mg, Na, K, Cl, Ca, and SO_4 were highest during the only under-ice lake-sampling campaign ever undertaken on Noell Lake; the exclusion of ions from ice during freeze-up is a well-established process in Arctic lakes (e.g., Welch and Bergmann, 1985; Belzile et al., 2002).

The hydrological regime of Noell Lake is influenced most strongly by minimal inputs of precipitation and the existence of expansive permafrost underlying most of the region. This situation magnifies the degree to which geomorphological parameters (i.e., disturbance, vegetation, parent materials) regulate the water chemistry of Arctic lakes in this region (Pienitz et al., 1997a; Rühland et al., 2003; Kokelj et al., 2005). The influence of sporadic fires has had a long-lasting impact on the landscape of the Noell Lake catchment region (Ritchie, 1984; Timoney et al., 1992; Landhausser and Wein, 1993; Payette et al., 2001; Lantz et al., 2010). In 1968, a wildfire burned from the area around Inuvik, NWT, north toward Noell Lake (Landhausser and Wein, 1993; Mackay, 1995). The intensity of the fire incinerated the existing vegetation and organic matter of the area, facilitating a deepening of the active layer and surface permafrost thaw (Mackay, 1995). Burned areas, characterized by dense alder and willow growth, are distinguishable from the unburned tundra (Landhausser and Wein, 1993). In the summer of 2012, lightning is believed to have been the cause of another wildfire that burned approximately 4000 ha of forest and vegetation around the Noell Lake area. Increased fluxes of dissolved organic carbon, dissolved nutrients, and ionic constituents were likely consequences of the wildfire (Carignan et al., 2000).

Schindler et al. (1974) suggest that steady increases in conductivity may also reflect anthropogenic disturbance in watersheds, identifying soil weathering as the likely cause of increased concentrations of major ions in lake water. While seasonal variations are important to consider, certain ionic species may have increased in Noell Lake since the 1980s—notably specific conductivity, Mg, SO_4, and Ca. Minimal industrial development had been undertaken in the catchment area until the spring of 2013, when construction began for an all-season road running directly through the catchment of Noell Lake.

Water Chemistry Comparison to Other Tundra Lakes

The water chemistry of Noell Lake was compared to the water chemistry of 27 other tundra lakes located east of the Mackenzie River Delta, NWT, and sampled in June and July from 2009 to 2011 by Houben et al. (2016). Additional comparisons were made to historical water chemistry values recorded on Noell Lake in the summer of 1986 by Anema et al. (1990b) and in July 2007 by Ogbebo et al. (2009a, b).

Mean July 2013 concentrations of DIC in Noell Lake (4.1 mg L^{-1}) were similar to those of the other upland lakes (Table 3), while concentrations of DOC (5.7 mg L^{-1}) in Noell Lake were significantly lower than both the mean and minimum concentrations of DOC for the other upland lakes. Similarly, Ogbebo et al. (2009a, b) reported concentrations of DIC (4.3 mg L^{-1}) and DOC (4.9 mg L^{-1}) in Noell Lake during July 2007. Mean July 2013 concentrations of TP (8.6 µg L^{-1}) and TN (251.0 µg L^{-1}) were significantly lower than those reported for the other upland lakes. Mean July 2007 concentrations reported by Ogbebo et al. (2009a, b) for Noell Lake (TP = 7.8 µg L^{-1} and TN = 201.5 µg L^{-1}) were also lower than concentrations reported by Houben et al. (2016). Furthermore, mean concentrations of TP and TN recorded during our study, as well as by Ogbebo et al. (2009a, b), were lower than the minimum concentrations recorded in the 27 upland lakes; this was also true for concentrations of DOC.

TABLE 3. Concentrations for water quality-related variables for 27 upland lakes located to the east of the Mackenzie Delta and sampled in June and July from 2009 to 2011.[1] Average concentrations are in mg L^{-1} except for specific conductivity (µS cm^{-1}), TN (µg L^{-1}), and TP (µg L^{-1}).

	Mean	Minimum	Maximum
DIC	4.2	0.7	14.5
DOC	17.5	9.6	36.4
TN	519.3	353.0	734.0
TP	29.9	10.6	67.9
Spec. cond.	87.1	31.0	220.8
Na	2.8	1.5	6.7
Mg	3.0	1.16	7.9
K	1.1	0.4	2.7
Cl	2.7	0.6	7.7
Ca	8.6	2.68	26.7
SO_4	10.9	0.3	47.5
SiO_2	1.6	0.2	3.4

[1] Data from Houben et al. (2016).

Mean concentrations of ionic species were generally similar in Noell Lake and the other upland lakes. The mean value of specific conductivity in Noell Lake was 79.9 µS cm^{-1} in July 2013, compared to 67.3 µS cm^{-1} in July 2007 (Ogbebo et al., 2009a, b), and 71.1 µS cm^{-1} in the summer of 1986 (Anema et al., 1990b). Mean July 2013 concentrations of Na, K, and SO_4 were 2.5, 1.1, and 11.3 mg L^{-1} respectively, and were similar to the concentrations in the other upland lakes. Ogbebo et al. (2009a, b) reported mean concentrations of 2.5 and 11.0 mg^{-1} for Na and SO_4 for Noell Lake in July 2007, while Anema et al. (1990b) reported concentrations of 2.4, 1.0, and 10.9 mg L^{-1} for Na, K, and SO_4 in the summer of 1986. Mean July 2013 concentrations of Mg, Cl, and Ca were 2.5, 1.8, and 7.3 mg L^{-1}, respectively; these concentrations, although lower than the concentrations of the other upland lakes, were still within the range. Ogbebo et al. (2009a, b) reported concentrations of Cl and Ca as 1.7 and 7.1 mg L^{-1} for Noell Lake in July of 2007, while Anema et al. (1990b) reported concentrations of 2.0, 2.1, and 7.0 mg L^{-1} for Mg, Cl, and Ca in the summer of 1986. Mean July 2013 concentrations of SiO_2 were 0.6 mg L^{-1} in Noell Lake while Ogbebo et al. (2009a, b) reported concentrations of SiO_2 as 0.4 mg L^{-1} in 2007; both of these concentrations are lower than the mean concentrations of the other upland lakes but higher than the reported minimum concentrations.

Open-Water Vertical Profiles

There is a distinct, observable divergence in limnological parameters at 12 m below the lake surface. During the open-water season of 1982, Read and Roberge (1986) used digital oxygen meters (YSI Model 58) to generate depth profiles of temperature and dissolved oxygen in Noell Lake over two separate days: 8 and 14 August 1982 (Fig. 10). Coincidentally, 8 August is the same day when depth profiles were recorded for this study. It is evident that at the time of sampling, Noell Lake was well mixed down to 10 m (the lowest sampled depth) in both years. However, the 1982 sampling campaign did not sample deep enough to capture the important stratification that was noted at approximately 12 m in the 2012 sampling campaign. Concentrations of dissolved oxygen at depth were lower in 2012 than they were in 1982.

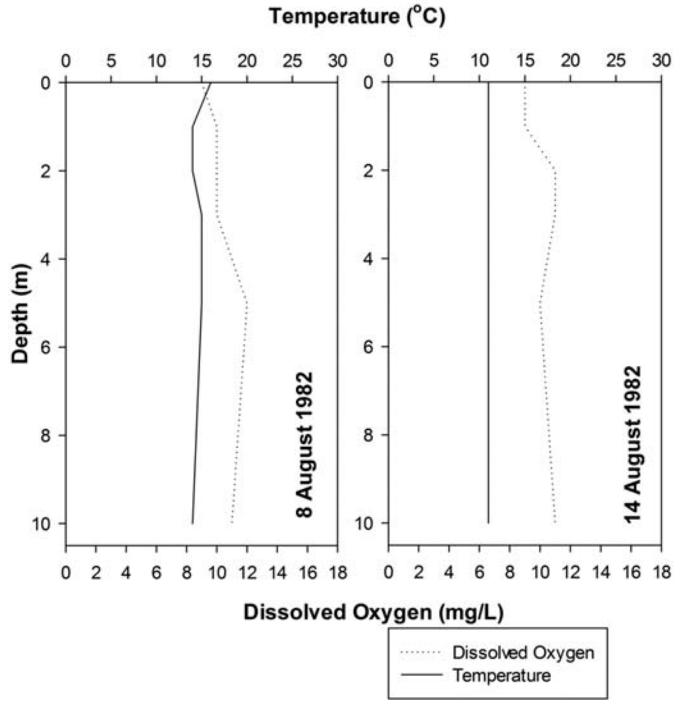


FIG. 10. Open-water temperature and dissolved oxygen profiles of Noell Lake, NWT, in 1982. Data from Read and Roberge (1986).

Under-Ice Depth Profiles

Under-ice lake profiles were more spatially heterogeneous than open-water lake profiles. Depth profiles of pH, dissolved oxygen, conductivity, and specific conductivity exhibited considerably more variability than open-water profiles with respect to different sample locations across Noell Lake. As reported in past northern limnological studies (e.g., Schindler et al., 1974; Deshpande et al., 2015), two conductivity maxima were observed under ice: one just beneath the ice and one towards the bottom of the lake. When the main volume of under-ice water is colder than 4˚C, water confined to the littoral areas of the lake can be heated slightly through the ice; warmer, denser water will sink and flow via currents of profile-bound density along the lake sediments to the deeper portion of Noell Lake (Bradley, 1969; Wetzel, 1983). Schindler et al. (1974) suggest that this same mechanism could transport solute-rich water, originating from freeze-out, to the deepest parts of the lake. These processes likely explain the steady increases in both conductivity and temperature observed in the hypolimnion during the under-ice season (Douglas and Smol, 1994).

Gravity currents induced by sediment mineralization—whereby waters enriched in salts are denser and thus flow from lake margins to the deepest regions of the lake—can cause similar processes with respect to cryoconcentration (Bradley, 1969; Welch and Bergmann, 1985). Similarly, Deshpande et al. (2015) reported that the highest specific conductivities at the bottom of thaw lakes were due to processes related to bacterial mineralization, while Terzhevik et al. (2009) reported oxygen-depleted waters flowing along lake margins and concentrating at the deepest part of Lake Vendyurskoe, Russia. In Noell Lake, the Near Buoy and Site 3 locations for lake profiles (Fig. 4) were both located at two of the three deepest holes of Noell Lake (Fig. 1), with the Near Buoy hole being the deepest part of Noell Lake. As a result, these locations recorded the highest under-ice values of specific conductivity and temperature while conversely recording the lowest concentrations and percent saturations of dissolved oxygen (Fig. 9).

Short-term Variability Under Lake Ice

On 28 November 2012, abrupt changes were observed to several key hydro-ecological parameters in the Noell Lake hypolimnion. Sudden simultaneous drops in hypolimnion oxygen concentrations and values of specific conductivity were accompanied by concomitant increases in hypolimnion water temperature. Over a 24 h period, hypolimnion water temperature increased from 1.16˚C to 2.26˚C, percent saturation of dissolved oxygen dropped from 90.6% to 66.7%, concentration of dissolved oxygen dropped from 12.82 to 9.15 mg L^{-1}, and specific conductivity decreased from 76.0 to 72.6 µS cm^{-1} (this was the lowest recorded value of specific conductivity for the whole under-ice season). These changes are significant when compared to the total range of values observed in the under-ice season. Using the onset of stratification to identify the beginning of the under-ice period (25 October 2012), we calculated the percentage of total seasonal change relative to the one-day event. Variations accounting for almost one-third of the entire range of values for these key limnological parameters were observed in a 24-hour period (37% of the total range in water temperature; 27% of the total range in specific conductivity; 30% of the total range in concentrations of dissolved oxygen; 31% of the total range in percent saturation of dissolved oxygen).

As specific conductivity in water near the ice increased as a result of processes related to cryoconcentration, water increased in density. Once enough salinity accumulated, the density was sufficient to cause water to abruptly sink to lower depths because of gravity currents. Deshpande et al. (2015) reported linkages between oxygen depletion, increases in specific conductivity, and increases in water temperature. The step-change drop in specific conductivity is interesting, and it is possible that these observed changes may be related to the movement of sensor location or depth. Alternatively, changes to specific conductivity could be related to salinity-temperature effects.

Changes to Thermal Stratification Impacting Dissolved Oxygen

Prior to this study, the degree to which Noell Lake stratifies was unknown, and similarly, the majority of Arctic lakes do not have data on inter- and intra-annual variability of vertical temperature distributions, especially under ice (Kirillin et al., 2012). Seasonal changes to the vertical temperature profile and mixing regime of a lake have important consequences to assessing water quality, local climatology, response to global warming, and the recreational potential of lakes (Kirillin et al., 2012). The distribution of oxygen affects the solubility of inorganic nutrients, which strongly impact the comportment, dispersal, and growth of organisms within the lake (Wetzel, 1983).

Broadly speaking, increasing water temperatures are likely to affect the water chemistry, nutrient status, and hydrology of lakes (Rouse et al., 1997), in turn affecting the aquatic biota that live in these ecosystems (Rühland et al., 2015). For example, extended and warmer open-water seasons have affected essential water column properties (e.g., light availability, nutrient distribution, stratification/mixing) and played a key role in influencing diatom community composition and dynamics (Rühland et al., 2013). More importantly, Rühland et al. (2015) suggest that climatically induced thresholds have been crossed in many lakes, and that ecological thresholds could be passed unexpectedly in the future.

As previously discussed, an important abiotic aquatic threshold is the development of hypoxic conditions in the bottom waters of stratified lakes (Wetzel, 1983). Typically, fish are thought to avoid severely hypoxic habitats via daily or seasonal migrations into more oxygenated water (Suthers and Gee, 1986). When physical migration is not possible, massive die-offs may occur (Vanni et al., 1990; Breitburg, 1992). By contrast, many aquatic invertebrates are tolerant of low oxygen conditions and use bottom waters that are low in oxygen as a refuge from fish predation (Lampert, 1989; Rahel and Kolar, 1990; Williamson, 1991). Like oxygen levels, temperatures exceeding certain thermal thresholds can alter fish activity and potentially have impacts on higher trophic organisms as well.

The development of stratification during the open-water season has significant consequences for the dynamics of dissolved oxygen and aquatic organisms. Continuous measurements highlighted the rapid response of dissolved oxygen to changes in stratification associated with mixing. In addition to temperature and density differences, winds play an important role in driving stratification response. Figure 11 demonstrates the relationship between ambient air temperature, wind speed, and stratification/mixing for the 3 m and 9 m depths in Noell Lake. A drop in air temperature from 2 to 11 August 2012 caused cooling of the epilimnion and reduced profile stability. Strong wind speeds, however, were the likely mechanism that triggered a full mixing of the water column, resulting in a convergence of 3 m and 9 m water temperatures (e.g., just before 13 August 2012).

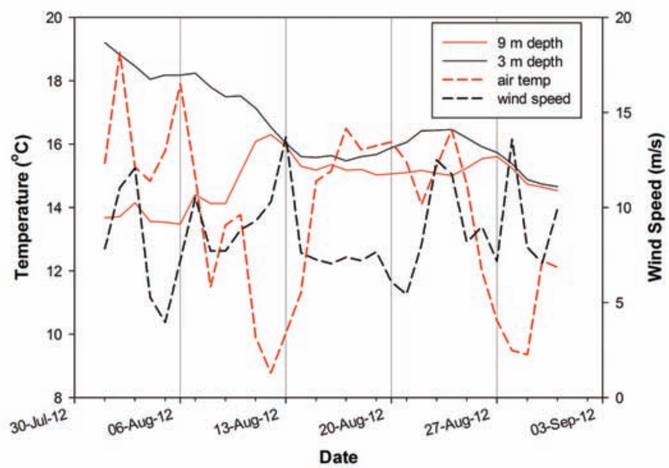


FIG. 11. Time series of air temperature (˚C) and wind speed (m/s), as measured by the Inuvik Airport Weather Station, and water temperature (˚C) measured at 3 m and 9 m below the water surface.

After 13 August 2012, air temperature rose and wind speed dropped. These changes allowed the upper layers to warm, as evidenced by the re-emergence of a separation of 3 m and 9 m water temperatures and re-establishment of thermal stratification. After 21 August, wind speed increased again to approximately the same speed that triggered the mixing event of 12 August; however, in this case mixing did not occur, and the separation between 3 m and 9 m temperatures continued. The difference was that air temperature remained elevated, which in turn kept the 3 m temperature elevated. Mixing did not occur again until air temperature dropped after 24 August. This pattern indicated that the wind speed required to drive lake mixing is a function of the strength of the stratification, and that, in fact, if the air temperature remains at or above the epilimnion temperature, winds below a certain speed will serve to enhance a stratified profile by more effectively transferring atmospheric heat into the epilimnion. Direction (not shown) was also noted to be important. Strong winds from the continental zone in August will advect in the warm air that is driving the warming of the surface layers, whereas strong winds from the north will bring cool air that in turn cools the epilimnion and, if the winds persist, will result in a mixing event. An interesting point here is that consideration of the mean wind state may not suffice to understand the response of a lake under climate change because lake thermal structure is clearly sensitive to day-to-day weather.

Future Applications of Automated Methods

Despite the abundance of tundra lakes throughout the Northern Hemisphere, little is known about how their physical, chemical, and hydro-ecological properties vary in response to seasonal climate patterns. In particular, we lack information for the winter months and have almost no information about continuous variations at the daily time scale. The sensitivity of tundra lake ecosystems to climate change has resulted in calls for paying greater attention to winter limnology and for establishing more continuous monitoring campaigns. Short-term changes in thermal stratification can lead to large, rapid changes in dissolved oxygen concentrations throughout the lake profile, and the dynamics of the relationship between wind speed and direction, air temperature, and lake temperatures/dissolved oxygen can be fully accessed only with continuous monitoring. Additionally, the importance of stratification during the winter was highlighted by the strong temperature gradient through the entire water column under ice-covered conditions. Winter data are important for documenting the conditions under ice, which can document the effects of climate change on lakes, as there are changes in the timing and duration of ice cover, the optical characteristics of ice cover, and increases in runoff to ice-covered lakes. Given the sensitivity of lake response to air temperature and winds, it would be reasonable to use projected trends in these parameters as a means to characterize potential future trajectories in lake state.

CONCLUSION

A study of the seasonal changes to limnological parameters of Noell Lake was undertaken using data collected from a series of automated and non-automated moorings. Past studies on Noell Lake involved analyzing samples of lake water for traditional physical and chemical parameters, indicative of only the days or hours before sampling. Moreover, there were no limnological measurements recorded during under-ice conditions.

Noell Lake was found to be strongly stratified throughout both the open-water and the under-ice seasons, with two prominent mixing periods in spring and fall. Processes of cryoconcentration and respiration intensified density-driven stratification under ice-covered conditions, with the deep holes of Noell Lake becoming particularly saline and oxygen-depleted all year. Hypoxia was prevalent during the under-ice season because the aforementioned physical and biogeochemical processes eliminated mixing from the lower lake depths while oxygen-demand remained high.

Use of continuous hourly monitoring allowed a better understanding of the dynamical response of Noell Lake to atmospheric forcing. Several processes that can be readily monitored by the automated and non-automated methods used in this analysis can form the basis for climate change analyses seeking to identify possible trajectories in lake state.

ACKNOWLEDGEMENTS

The authors thank the Aurora Research Institute for their logistical and technical support for this project. We are grateful for the assistance of Don Ross, Erika Hille, Jimmy Ruttan, William Hurst, Paul Moquin, and Laurent de Rham. We thank the three anonymous reviewers for their helpful comments.

APPENDIX 1

The following tables are available in a supplementary file to the online version of this article at:
http://arcticjournalhosting.ucalgary.ca/arctic/index.php/arctic/rt/suppFiles/4716/0

TABLE S1. Chemical and nutrient analyses of water samples removed from various locations and depths of Noell Lake on 17 September 2011.

TABLE S2. Chemical and nutrient analyses of water samples removed from various locations and depths of Noell Lake on 13 May 2012.

TABLE S3. Chemical analyses of water samples removed from various locations and depths of Noell Lake on 26 June 2012.

TABLE S4. Chemical and nutrient analyses of water samples removed from various locations and depths of Noell Lake on 19 November 2012.

TABLE S5. Chemical and nutrient analyses of water samples removed from various locations and depths of Noell Lake on 15 July 2013.

REFERENCES

Anema, C., Hecky, R.E., Fee, E.J., Nernberg, D., and Guildford, S.J. 1990a. Water chemistry of some lakes and channels in the Mackenzie Delta and on the Tuktoyaktuk Peninsula, N.W.T., 1985. Winnipeg, Manitoba: Central and Arctic Region, Fisheries and Oceans Canada.
http://publications.gc.ca/collections/collection_2007/dfo-mpo/Fs97-13-726E.pdf

Anema, C., Hecky, R.E., Himmer, S., and Guildford, S.J. 1990b. Water chemistry of some lakes and channels in the Mackenzie Delta and on the Tuktoyaktuk Peninsula, N.W.T., 1986. Winnipeg, Manitoba: Central and Arctic Region, Fisheries and Oceans Canada.
http://www.dfo-mpo.gc.ca/Library/115234.pdf

Antoniades, D., Douglas, M.S.V., and Smol, J.P. 2005. Quantitative estimates of recent environmental changes in the Canadian High Arctic inferred from diatoms in lake and pond sediments. Journal of Paleolimnology 35(3):349 – 360.
https://doi.org/10.1007/s10933-004-6611-3

Bailey, R.C., Norris, R.H., and Reynoldson, T.B. 2004. Bioassessment of freshwater ecosystems using the reference condition approach. New York: Springer.
https://doi.org/10.1007/978-1-4419-8885-0

Belzile, C., Gilson, J.A.E., and Vincent, W.F. 2002. Colored dissolved organic matter and dissolved organic carbon exclusion from lake ice: Implications for irradiance transmission and carbon cycling. Limnology and Oceanography 47(5):1283 – 1293.
https://doi.org/10.4319/lo.2002.47.5.1283

Bradley, W.H. 1969. Vertical density currents - II. Limnology and Oceanography 14(1):1 – 3.
https://doi.org/10.4319/lo.1969.14.1.0001

Breitburg, D.L. 1992. Episodic hypoxia in the Chesapeake Bay: Interacting effects of recruitment, behavior, and physical disturbance. Ecological Monographs 62(4):525 – 546.
https://doi.org/10.2307/2937315

Brunberg, A.-K., Nilsson, E., and Blomqvist, P. 2002. Characteristics of oligotrophic hardwater lakes in a postglacial land-rise area in mid-Sweden. Freshwater Biology 47(8):1451 – 1462.
https://doi.org/10.1046/j.1365-2427.2002.00881.x

Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K.M., Brown, C., et al. 2011. The pace of shifting climate in marine and terrestrial ecosystems. Science 334(6056):652 – 655.
https://doi.org/10.1126/science.1210288

Carignan, R., D'Arcy, P., and Lamontagne, S. 2000. Comparative impacts of fire and forest harvesting on water quality in Boreal Shield lakes. Canadian Journal of Fisheries and Aquatic Sciences 57(S2):105 – 117.
https://doi.org/10.1139/f00-125

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., et al. 2013. Long-term climate change: Projections, commitments and irreversibility. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M., eds. Climate change 2013: The physical science basis. Working Group Contribution I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press. Chapter 12: 1029 – 1136.

Cornwell, J.C. 1992. Cation export from Alaskan Arctic watersheds. Hydrobiologia 240(1-3):15 – 22.
https://doi.org/10.1007/BF00013448

Cremer, H., Bennike, O., Håkansson, L., Hultzsch, N., Klug, M., Kobabe, S., and Wagner, B. 2005. Hydrology and diatom phytoplankton of High Arctic lakes and ponds on Store Koldewey, Northeast Greenland. International Review of Hydrobiology 90(1):84 – 99.
https://doi.org/10.1002/iroh.200410738

de Rham, L., and Carter, T. 2009. Bathymetry of Noell Lake, Northwest Territories Canada. Unpubl. report available from Water & Climate Impacts Research Centre, Environment Canada, University of Victoria, PO Box 3060, Station CSC, Victoria, British Columbia V8V 3R4.

Deshpande, B.N., MacIntyre, S., Mateev, A., and Vincent, W.F. 2015. Oxygen dynamics in permafrost thaw lakes: Anaerobic bioreactors in the Canadian Subarctic. Limnology and Oceanography 60(5):1656 – 1670.
https://doi.org/10.1002/lno.10126

Diffenbaugh, N.S., and Giorgi, F. 2012. Climate change hotspots in the $CMIP_5$ global climate model ensemble. Climatic Change 114(3-4):813 – 822.
https://doi.org/10.1007/s10584-012-0570-x

Douglas, M.S.V., and Smol, J.P. 1994. Limnology of high Arctic ponds (Cape Herschel, Ellesmere Island, N.W.T.) Archiv für Hydrobiologie 131:401 – 434.

Environment Canada. 1992. Analytical methods manual. Ottawa: Inland Waters Directorate, Water Quality Branch, Environment Canada.

———. 2012. Canadian climate normals 1981–2010. http://climate.weather.gc.ca/climate_normals/index_e.html

Evans, M.S., and Grainger, E.H. 1980. Zooplankton in a Canadian Arctic estuary. In: Kennedy, V.S., ed. Estuarine perspectives. Waltham, Massachusetts: Academic Press-Elsevier Inc. 199–210. https://doi.org/10.1016/B978-0-12-404060-1.50025-3

Hobbie, J.E. 1984. Polar limnology. In: Taub, F.B., ed. Ecosystems of the World, 23: Lakes and reservoirs. Amsterdam: Elsevier Science Publishers. 63–105.

Houben, A.J., French, T.D., Kokelj, S.V., Wang, X., Smol, J.P., and Blais, J.M. 2016. The impacts of permafrost thaw slump events on limnological variables in upland tundra lakes, Mackenzie Delta region. Fundamentals of Applied Limnology 189(1):11–35. https://doi.org/10.1127/fal/2016/0921

Kirillin, G., Leppäranta, M., Terzhevik, A., Granin, N., Bernhardt, J., Engelhardt, C., Efremova, T., et al. 2012. Physics of seasonally ice-covered lakes: A review. Aquatic Sciences 74(4):659–682.

Kling, G.W., Kipphut, G.W., and Miller, M.C. 1992. The flux of CO_2 and CH_4 from lakes and rivers in Arctic Alaska. Hydrobiologia 240(1-3):23–36. https://doi.org/10.1007/BF00013449

Kokelj, S.V., Jenkins, R.E., Milburn, D., Burn, C.R., and Snow, N. 2005. The influence of thermokarst disturbance on the water quality of small upland lakes, Mackenzie Delta region, Northwest Territories, Canada. Permafrost and Periglacial Processes 16(4):343–353. https://doi.org/10.1002/ppp.536

Lampert, W. 1989. The adaptive significance of diel vertical migration of zooplankton. Functional Ecology 3(1):21–27. https://doi.org/10.2307/2389671

Landhausser, S.M., and Wein, R.W. 1993. Postfire vegetation recovery and tree establishment at the Arctic treeline: Climate-change-vegetation-response hypotheses. Journal of Ecology 81(4):665–672. https://doi.org/10.2307/2261664

Lantz, T.C., Gergel, S.E., and Henry, G.H.R. 2010. Response of green alder (*Alnus viridis* subsp. *fruticosa*) patch dynamics and plant community composition to fire and regional temperature in north-western Canada. Journal of Biogeography 37(8):1597–1610. https://doi.org/10.1111/j.1365-2699.2010.02317.x

LaPerriere, J.D., Jones, J.R., and Swanson, D.K. 2003. Limnology of lakes in Gates of the Arctic National Park and Preserve, Alaska. Lake and Reservoir Management 19(2):108–121. https://doi.org/10.1080/07438140309354077

Lim, D.S.S., and Douglas, M.S.V. 2003. Limnological characteristics of 22 lakes and ponds in the Haughton Crater region of Devon Island, Nunuvut, Canadian High Arctic. Arctic, Antarctic, and Alpine Research 35(4):509–519. https://doi.org/10.1657/1523-0430(2003)035[0509:LCOLAP]2.0.CO;2

Løvik, J.E., and Kjellberg, G. 2003. Long-term changes of the crustacean zooplankton community in Lake Mjøsa, the largest lake in Norway. Journal of Limnology 62(2):143–150. https://doi.org/10.4081/jlimnol.2003.143

Luoto, T.P. 2009. Subfossil Chironomidae (Insecta: Diptera) along a latitudinal gradient in Finland: Development of a new temperature inference model. Journal of Quaternary Science 24(2):150–158. https://doi.org/10.1002/jqs.1191

MacDonald, L.A., Balasubramaniam, A.M., Hall, R.I., Wolfe, B.B., and Sweetman, J.N. 2012. Developing biomonitoring protocols for shallow Arctic lakes using diatoms and artificial substrate samplers. Hydrobiologia 683(1):231–248. https://doi.org/10.1007/s10750-011-0960-5

Mackay, J.R. 1995. Active layer changes (1968 to 1993) following the forest-tundra fire near Inuvik, NWT, Canada. Arctic and Alpine Research 27(4):323–336. https://doi.org/10.2307/1552025

Moiseenko, T.I., Sharov, A.N., Vandish, O.I., Kudryavtseva, L.P., Gashkina, N.A., and Rose, C. 2009. Long-term modification of Arctic lake ecosystems: Reference condition, degradation under toxic impacts and recovery (case study Imandra Lakes, Russia). Limnologica – Ecology and Management of Inland Waters 39(1):1–13. https://doi.org/10.1016/j.limno.2008.03.003

Ogbebo, F.E., Evans, M.S., Brua, R.B., and Keating, J.J. 2009a. Limnological features and models of chlorophyll-a in 30 lakes located in the lower Mackenzie River basin, Northwest territories (Canada). Journal of Limnology 68(2):336–351. https://doi.org/10.4081/jlimnol.2009.336

Ogbebo, F.E., Evans, M.S., Waiser, M.J., Tumber, V.P., and Keating, J.J. 2009b. Nutrient limitation of phytoplankton growth in Arctic lakes of the lower Mackenzie River Basin, northern Canada. Canadian Journal of Fisheries and Aquatic Sciences 66(2):247–260. https://doi.org/10.1139/F08-202

Payette, S., Fortin, M.-J., and Gamache, I. 2001. The Subarctic forest-tundra: The structure of a biome in a changing climate: The shifting of local subarctic tree lines throughout the forest-tundra biome, which is linked to ecological processes at different spatiotemporal scales, will reflect future global changes in climate. BioScience 51(9):709–718. https://doi.org/10.1641/0006-3568(2001)051[0709:TSFTTS]2.0.CO;2

Pienitz, R., Smol, J.P., and Lean, D.R.S. 1997a. Physical and chemical limnology of 59 lakes located between the southern Yukon and the Tuktoyaktuk Peninsula, Northwest Territories (Canada). Canadian Journal of Fisheries and Aquatic Sciences 54(2):330–346. https://doi.org/10.1139/f96-274

———. 1997b. Physical and chemical limnology of 24 lakes located between Yellowknife and Contwoyto Lake, Northwest Territories (Canada). Canadian Journal of Fisheries and Aquatic Sciences 54(2):347–358. https://doi.org/10.1139/f96-275

Quinton, W.L., and Marsh, P. 1999. A conceptual framework for runoff generation in a permafrost environment. Hydrological Processes 13(16):2563 – 2581.
https://doi.org/10.1002/(SICI)1099-1085(199911)13:16<2563::AID-HYP942>3.0.CO;2-D

Rahel, F.J., and Kolar, C.S. 1990. Trade-offs in the response of mayflies to low oxygen and fish predation. Oecologia 84(1):39 – 44.
https://doi.org/10.1007/BF00665592

Ramlal, P.S., Anema, C., Cummings, E., Fee, E.J., Guildford, S.J., Hallard, K., Hecky, R.E., et al. 1991. Macrophyte and algal studies of some lakes in the Mackenzie Delta and on the Tuktoyaktuk Peninsula, 1985 – 86. Canadian Data Report of Fisheries and Aquatic Sciences 839. Winnipeg, Manitoba: Central and Arctic Region Department of Fisheries and Oceans.
http://publications.gc.ca/collections/collection_2013/mpo-dfo/Fs97-13-839-eng.pdf

Read, C.J., and Roberge, M.M. 1986. Creel census and biological investigation of Noell Lake, Campbell Lake and Campbell Creek, Northwest Territories. Canadian Data Report of Fisheries and Aquatic Sciences 571. Winnipeg, Manitoba: Western Region Department of Fisheries and Oceans.
http://publications.gc.ca/collections/collection_2013/mpo-dfo/Fs97-13-571-eng.pdf

Ritchie, J.C. 1984. Past and present vegetation of the far northwest of Canada. Toronto: University of Toronto Press.

Rühland, K.M., Smol, J.P., Wang, X., and Muir, D.C.G. 2003. Limnological characteristics of 56 lakes in the Central Canadian Arctic treeline region. Journal of Limnology 62(1):9 – 27.
https://doi.org/10.4081/jlimnol.2003.9

Rühland, K.M., Paterson, A.M., Keller, W., Michelutti, N., and Smol, J.P. 2013. Global warming triggers the loss of a key Arctic refugium. Proceedings of the Royal Society B 280: 2013.1887.
https://doi.org/10.1098/rspb.2013.1887

Rühland, K.M., Paterson, A.M., and Smol, J.P. 2015. Lake diatom responses to warming: Reviewing the evidence. Journal of Paleolimnology 54(1):1 – 35.
https://doi.org/10.1007/s10933-015-9837-3

Schindler, D.W., Welch, H.E., Kalff, J., Brunskill, G.J., and Kritsch, N. 1974. Physical and chemical limnology of Char Lake, Cornwallis Island (75˚ N Lat.). Journal of the Fisheries Research Board of Canada 31(5):585 – 607.
https://doi.org/10.1139/f74-092

Settele, J., Scholes, R., Betts, R.A., Bunn, S., Leadley, P., Nepstad, D., Overpeck, J.T., and Taboada, M.A. 2014. Terrestrial and inland water systems. In Field, C.B., and Barros, V.R., eds. Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press. 271 – 359.

Smol, J.P., and Douglas, M.S.V. 2007. From controversy to consensus: Making the case for recent climate change in the Arctic using lake sediments. Frontiers in Ecology and the Environment 5(9):466 – 474.
https://doi.org/10.1890/060162

Suthers, I.M., and Gee, J.H. 1986. Role of hypoxia in limiting diel spring and summer distribution of juvenile yellow perch (*Perca flavescens*) in a prairie marsh. Canadian Journal of Fisheries and Aquatic Sciences 43(8):1562 – 1570.
https://doi.org/10.1139/f86-194

Terzhevik, A., Golosov, S., Palshin, N., Mitrokhov, A., Zdorovennov, R., Zdorovennova, G., Kirillin, G., Shipunova, E., and Zverev, I. 2009. Some features of the thermal and dissolved oxygen structure in boreal, shallow ice-covered Lake Vendyurskoe, Russia. Aquatic Ecology 43(3):617 – 627.
https://doi.org/10.1007/s10452-009-9288-x

Timoney, K.P., La Roi, G.H., Zoltai, S.C., and Robinson, A.L. 1992. The high subarctic forest-tundra of northwestern Canada: Position, width, and vegetation gradients in relation to climate. Arctic 45(1):1 – 9.
https://doi.org/10.14430/arctic1367

Vanni, M.J., Luecke, C., Kitchell, J.F., Allen, Y., Temte, J., and Magnuson, J.J. 1990. Effects on lower trophic levels of massive fish mortality. Nature 344:333 – 335.
https://doi.org/10.1038/344333a0

Vincent, W.F., Laurion, I., Pienitz, R., and Anthony, K.M.W. 2012. Climate impacts on Arctic lake ecosystems. In: Goldman, C.R., Kumagai, M., and Robarts, R.D., eds. Climatic change and global warming of inland waters: Impacts and mitigation for ecosystems and societies. Hoboken, New Jersey: John Wiley & Sons, Ltd. 27 – 42.
https://doi.org/10.1002/9781118470596.ch2

Welch, H.E. 1974. Metabolic rates of Arctic lakes. Limnology and Oceanography 19(1):65 – 73.
https://doi.org/10.4319/lo.1974.19.1.0065

Welch, H.E., and Bergmann, M.A. 1985. Water circulation in small Arctic lakes in winter. Canadian Journal of Fisheries and Aquatic Sciences 42(3):506 – 520.
https://doi.org/10.1139/f85-068

Welch, H.E., and Legault, J.A. 1986. Precipitation chemistry and chemical limnology of fertilized and natural lakes at Saqvaqjuac, N.W.T. Canadian Journal of Fisheries and Aquatic Sciences 43(6):1104 – 1134.
https://doi.org/10.1139/f86-140

Westover, K.S., Moser, K.A., Porinchu, D.F., MacDonald, G.M., and Wang, X. 2009. Physical and chemical limnology of a 61-lake transect across mainland Nunavut and southeastern Victoria Island, Central Canadian Arctic. Fundamental and Applied Limnology 175(2):93 – 112.
https://doi.org/10.1127/1863-9135/2009/0175-0093

Wetzel, R.G. 1983. Limnology. Toronto: W.B. Saunders Company. 743 p.

Whalen, S.C., and Cornwell, J.C. 1985. Nitrogen, phosphorus, and organic carbon cycling in an Arctic lake. Canadian Journal of Fisheries and Aquatic Sciences 42(4):797 – 808.
https://doi.org/10.1139/f85-102

Williamson, C.E. 1991. Copepoda. In: Thorp, J.H., and Covich, A.P., eds. Ecology and classification of North American freshwater invertebrates, 1st ed. New York: Academic Press. 787 – 822.